PNNL-25833

Pacific Northwest NATIONAL LABORATORY

Light Water Reactor Sustainability Program

Status Report and Research Plan for Cables Harvested from Crystal River Unit 3 Nuclear Generating Plant

September 2016

U.S. Department of Energy

Office of Nuclear Energy

PNNL-25833

Status Report and Research Plan for Cables Harvested from Crystal River Unit 3 Nuclear Generating Plant

Leonard S. Fifield

September 2016

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy

Light Water Reactor Sustainability Program

Status Report and Research Plan for Cables Harvested from Crystal River Unit 3 Nuclear Generating Plant

M3LW-16OR04040110
PNNL-25833

September 2016

Approved by:

Steve Schlahta, Director
Nuclear Science Project Management Office

9/19/16
Date

ABSTRACT

Harvested cables from operating or decommissioned nuclear power plants present an important opportunity to validate models, understanding material aging behavior, and validate characterization techniques. Crystal River Unit 3 Nuclear Generating Plant is a pressurized water reactor that was licensed to operate from 1976 to 2013. Cable segments were harvested and made available to the Light Water Reactor Sustainability research program through the Electric Power Research Institute. Information on the locations and circuits within the reactor from whence the cable segments came, cable construction, sourcing and installation information, and photographs of the cable locations prior to harvesting were provided. The cable variations provided represent six of the ten most common cable insulations in the nuclear industry and experienced service usage for periods from 15 to 42 years. Subsequently, these cables constitute a valuable asset for research to understand aging behavior and measurement of nuclear cables.

Received cables harvested from Crystal River Unit 3 Nuclear Generating Plant consist of low voltage, insulated conductor surrounded by jackets in lengths from 24 to 100 feet each. Cable materials will primarily be used to investigate aging under simultaneous thermal and gamma radiation exposure. Each cable insulation and jacket material will be characterized in its as-received condition, including determination of the temperatures associated with endothermic transitions in the material using differential scanning calorimetry and dynamic mechanical analysis. Temperatures for additional thermal exposure aging will be selected following the thermal analysis to avoid transitions in accelerated laboratory aging that do not occur in field conditions. Aging temperatures above thermal transitions may also be targeted to investigate the potential for artifacts in lifetime prediction from rapid accelerated aging. Total gamma doses and dose rates targeted for each material will be determined based on filling gaps in prior work, known limits of material classes and resource constraints. Experimental plans will be developed in the context of existing data for the insulation and jacket materials available in published Department of Energy and Electric Power Research Institute reports toward addressing identified knowledge gaps.

CONTENTS

FIGURES

TABLES

ACRONYMS

BIW	Boston Insulated Wire & Cable Company
CPE	chlorosulphonated polyethylene
CR3	Crystal River 3 Nuclear Generating Station
CSPE	chlorosulphonated polyethylene
DMA	dynamic mechanical analyzer
DOE	Department of Energy
DSC	differential scanning calorimetry
EAB	elongation at break
EP	ethylene-propylene
EPR	ethylene-propylene rubber
EPRI	Electric Power Research Institute
EPDM	ethylene-propylene-diene M-type (ASTM D1418, 2010)
FDR	frequency domain reflectometry
FMR	fire and moisture resistant
FR	flame retardant
FWIII	Firewall® III
HTK	Kerite high temperature EPR-like insulation
ID	identifier
IM	indenter modulus
LWRS	Light Water Reactor Sustainability
NOS	new old stock
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PSRC	Pacific-Sierra Research Corporation
SCRAPS	Sandia's Cable Repository of Aged Polymer Samples
Ski	Ingemansson Technology
UConn	University of Connecticut
XLPE	cross-linked polyethylene
XLPO	cross-linked polyolefin

INTRODUCTION

A significant challenge to pursuing new investigations in the aging behavior of electrical cables systems in existing nuclear power plants (NPPs) relevant to subsequent license renewal (SLR) is the availability of insulation and jacket material to study. Chemical formulations of polymer systems have changed since the 1960s, 1970s and 1980s as manufacturers have improved materials and cable construction. Most cables manufactured today, therefore, may exhibit very different aging behavior then older cables still in service. Procuring baseline cable stock that was manufactured using vintage materials and processes, but never used in service, so called 'new old stock' (NOS) cable, is particularly difficult as sources for this material become less available over time. Harvested cable, or cable that has been placed in service in a NPP, is valuable to understand cable aging in the actual environment and to verify models and assessment methods, but is similarly difficult to come by.

In 2015, the Electric Power Research Institute (EPRI) established a cable harvesting project to obtain service-aged cables for research to support EPRI members who were looking to re-license their nuclear plants from 60 to 80 years (Long Term Operation (LTO)). A research coordination and collaboration group was previously including EPRI, the Department of Energy (DOE) Office of Nuclear Energy Light Water Reactor Sustainability (LWRS) Cable Program, and the Nuclear Regulatory Commission (NRC) Office of Research to minimize duplicate lines of research on cable LTO. Group members individually pursued means to obtain legacy cables from operating plants to support research plans. To supplement the limited supply of cables that were able to be harvested from Zion Nuclear Station, EPRI pursued harvesting cables from Crystal River 3 Nuclear Generating Plant (CR3) and was able to harvest cable in sufficient amounts to begin time-critical, long term research. Cables samples harvested through EPRI and provided to the LWRS program include six of the ten most low-voltage common insulations in containment in NPPs in the United States. The lot includes cables manufactured by Anaconda Wire & Cable Company (Anaconda), Boston Insulated Wire & Cable Company (BIW), Brand Rex, Inc. (Brand Rex), Kerite Company (Kerite), The Okonite Company (Okonite), and The Rockbestos Company (Rockbestos). The five besides BIW represent the five most common insulations. Kerite HTK insulation is of particular interest because it is commonly found in containment, but its aging behavior is relatively unstudied.

Cable materials harvested from CR3 for the DOE research are indicated in right hand column of Table 1.The most common insulation materials for cables in containment according to a 1994 EPRI report [EPRI TR-103841] are listed in the left hand column of Table 1 in descending order. Rank is based on number of the 106 reactors (operating or under construction) surveyed containing identified cable. All of the cable insulations are members of either the cross-linked polyethylene/polyolefin (XLPE/XLPO) or the ethylene-propylene rubber (EP or EPR) classes of materials. HTK is a Kerite high temperature, "EPR-like" material. FR stands for flame retardant and FMR for flame and moisture resistant. The right hand column of Table 1 also summarizes the jacket materials for the cables harvested from CR3: chlorosulphonated polyethylene (CSPE) and chlorinated polyethylene (CPE).

Table 1. Ranking of Most Common Cable Insulations found in Containment

Rank	**Cable**	**# Units**	**CR3 ID**	**Manufacturer (Insulation/Jacket)**
1	Rockbestos Firewall III (XLPE)	61	CIS1	Rockbestos Firewall III (XLPE/CSPE)
2	Anaconda EPR	35	RCR296	Anaconda (FR-EP/CPE)
3	Brand-Rex XLPE	30	FWA75	Brand-Rex (FR-XLPE/CSPE)
4	Okonite EPR	26	EFC51	Okonite (EP-FMR/CSPE)
5	Kerite HTK	25	ARE41	Kerite (HTK/FR)
6	Rockbestos Coax	24	--	
7	Raychem XLPE	23	--	

8	Samuel Moore EPR	19	--	
9	BIW Bostrad 7E	19	RCR283,4	BIW (EPR/CSPE)
10	Kerite FR	13		--

SUMMARY OF HARVESTED CR3 CABLES

The following summaries present example data provided through EPRI for each of the cable sample received. In addition, circuit diagrams, installation records, location condition information, and photographs of in-plant locations of the cables prior to harvesting were provided.

ANACONDA (FR-EP/CPE)

The 24 foot long, green-jacketed Anaconda 600V Instrument cable provided (CR3 ID RCR296), seen in Figure 1, is of shielded twisted quad (STQ) (four conductor) construction. Each conductor is 16 American wire gauge (AWG) and the copper drain wire is 18 AWG. The jacket is labeled "ANACONDA-Y 4/C #16 FLAME-GUARD FR-EP 600V". Jacket material is 55 mil CPE and insulation is 26 mil EPR. The cable was manufactured in February of 1985, installed in CR3 in April of 1985, and saw 30 years of service in the Reactor Coolant system with operational current less than 5 mA, operational voltage of 5 VDC, and 100% duty factor. It was designated as Safety Related and under Maintenance Rule. Anaconda EPR is the second most common insulation in containment, found in one-third of plants.

Figure 1. Anaconda (FR-EP/CPE) (RCR296) Cable from CR3

BIW (EPR/CSPE)

The 112 foot long, green-jacketed Brand Rex Instrumentation cable provided (CR3 ID FWA75), seen in Figure 2, is of shielded twisted pair (STP) (two conductor) construction. Each conductor is 16 AWG and the copper drain wire is 18 AWG. The jacket is labeled "BIW CABLE SYSTEMS, INC. BOSTRAD 7E 16 AWG ITSP EPR-CSPE INS/CSPE JKT 600V INST". Jacket material is 59 mil CSPE and insulation is 28 mil EPR. The cable was manufactured in February of 1983, installed in CR3 in April of 1985, and saw 30 years of service in the Reactor Coolant system with operational current 4-20 mA, operational voltage of 24 VDC, and 100% duty factor. It was designated as Safety Related, and was under Maintenance Rule. BIW EPR is the ninth most common insulation in containment, found in 19% of plants.

Figure 2. BIW (EPR/CSPE) (FWA75) Cable from CR3

BRAND REX (FR-XLPE/CSPE)

The two 24 foot long, black-jacketed BIW Control & Instrument Wiring cables provided (CR3 IDs RCR283, RCR284), seen in Figure 3, are of STP construction. Each conductor is 16 AWG. The jacket is labeled "BRAND-REX ULTROL INSTRUMENTATION CABLE 600V 1 SHIELDED PR #16 AWG". Jacket material is 45 mil CSPE and insulation is 25 mil XLPE. The cable was manufactured in April of 1986, installed in CR3 in September of 1994, and saw 21 years of service in the Main Feedwater system with operational current 4-20 mA, operational voltage of 24 VDC, and 100% duty factor. It was not designated as Safety Related, but was under Maintenance Rule. Brand Rex XLPE is the third most common insulation in containment, found in 28% of plants.

Figure 3. Brand Rex (FR-XLPE/CSPE) (RCR283) Cable from CR3

KERITE (HTK/FR)

The 100 foot long, black-jacketed Kerite 1kV Power & 600V Control cable provided (CR3 ID ARE41), seen in Figure 4, comprises two 10AWG copper conductors. The jacket is not labeled. Jacket material is 63 mil Kerite FR and insulation is 63 mil Kerite HT Oil Base Compound. The cable was manufactured in March of 1971, installed in CR3 in July of 1973, and saw 42 years of service in the Condenser Air Removal system with operational current 15 A, operational voltage of 125 VDC, and 100% duty factor. It was not designated as Safety Related, and was not under Maintenance Rule. Kerite HTK is the fifth most common insulation in containment, found in one-fifth of US plants. The ARE41 Kerite cable has an asbestos filler between the insulated conductors and the jacket. The asbestos filler will be removed (abated) from the cable and the insulation and jacket components tested and certified to be asbestos-free prior to dissection.

Figure 4. Kerite (HTK/FR) (ARE41) Cable from CR3

OKONITE (EP-FMR/CSPE)

The 68 foot long, black-jacketed Okonite Power & Control cable provided (CR3 ID EFC51), seen in Figure 5, is composed of three 14 AWG. The jacket is labeled "OKONITE 4 3/C 14 AWG CU OKONITE FMR (EP)-CSPE 600V 18C 1998". Jacket material is 45 mil Okolon CSPE and insulation is 40 mil Okonite FMR EPR. The cable was manufactured in February of 1998, installed in CR3 in September of 1999, and saw 15 years of service in the Emergency Feedwater system with operational current 0.1 A, operational voltage of 120 VAC, and 100% duty factor. It was designated as Safety Related, and was under Maintenance Rule. Okonite EPR is the fourth most common insulation in containment, found in 25% of plants.

Figure 5. Okonite (EP-FMR/CSPE) (EFC51) Cable from CR3

ROCKBESTOS FIREWALL III (XLPE/CSPE)

The 56 foot long, black-jacketed Rockbestos 600V Power, Control, and Instrument and SIS cable provided (CR3 IDs CIS1), seen in Figure 6, is of STP construction. Each conductor is 16 AWG and the copper drain wire is 18 AWG. The jacket is labeled "2/C 16 AWG ROCKBESTOS® 600V B/M NO. NK-35A". Jacket material is 45 mil Hypalon CSPE and insulation is 25 mil XLPE. The cable was manufactured in February of 1993, installed in CR3 in March of 1994, and saw 21 years of service in the Industrial Cooling system with operational current in the mA, operational voltage of 24 VDC, and 100% duty factor. It was not designated as Safety Related, but was under Maintenance Rule. Rockbestos XLPE is the most common insulation in containment, found in 58% of plants.

Figure 6. Rockbestos Firewall III (XLPE/CSPE) (CIS1) Cable from CR3

RESEARCH PLANS FOR CR3 CABLE TESTING

Harvested cable materials will primarily be used to investigate aging under simultaneous thermal and gamma radiation exposure. Each cable insulation and jacket material will initially be characterized in its as-received condition including frequency domain reflectometry (FDR) and indenter modulus (IM) mapping of the intact cables. Jacketing will be removed from insulated conductors. Metallic conductors will be removed from the majority of the insulation so that the insulation may be tensile tested. Intact insulated conductors will also be IM measured. Additional characterization of the insulation and jacket materials will include determination of the temperatures associated with endothermic transitions in the material using differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA). Temperatures for additional thermal exposure aging will be selected following the thermal analysis to avoid transitions in accelerated laboratory aging that do not occur in field conditions. Aging temperatures above thermal transitions may also be targeted to investigate the potential for artifacts in lifetime prediction from rapid accelerated aging.

For example, the DSC curve for Rockbestos Firewall® III XLPE in Figure 7 shows heat flow transitions between 100°C and 124°C. Long term operation of the cable will occur and temperatures below its 90°C temperature rating. Accelerated laboratory aging above 100°C will be performed above a phase transition in the material and therefore may not be representative of degradation behavior characteristic of service in the field.

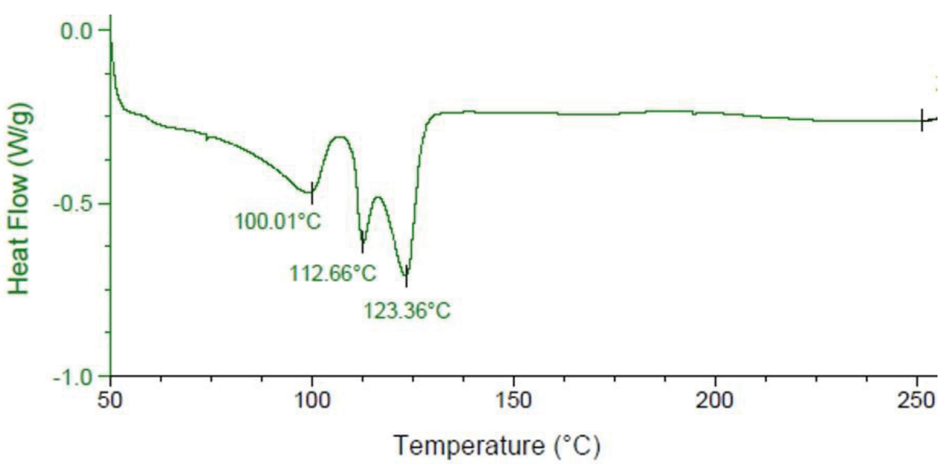

Figure 7. DSC curve of Firewall® III XLPE heated in nitrogen at 10K/minute.

Total gamma doses and dose rates targeted for each material will be determined based on filling gaps in prior work, known limits of material classes and resource constraints. Experimental plans will be developed in the context of existing data for the insulation and jacket materials available in published DOE and EPRI reports toward addressing identified knowledge gaps.

The Sandia's Cable Repository of Aged Polymer Samples (SCRAPS) aging database [SAND2005-7331] reports combined thermal and gamma radiation aging of nuclear cable insulation and jacket materials. Table 2 lists exposures conditions explored in that work on cables that are understood to correlated with insulation materials found in the CR3 harvested cables. Correlated data is for insulation materials that are understood to have been completely separated from conductor, jacket, etc. and prior to aging. Entries with dose rate of 0 indicate thermal only aging. The other aging entries are understood to represent combined, simultaneous aging of insulation samples at the indicated temperatures and gamma dose rates. Of the six cable insulation materials received from CR3, Kerite HTK does not seem to be represented in the SCRAPS data and BIW data is for jacket only, not insulation. Planned research with the CR3 materials will provide information on simultaneous thermal and radiation aging for Kerite HTK and BIW EPR insulations, as well as additional exposure conditions for the other materials included in SCRAPS.

Table 2. Summary of Information in SCRAPS Database for CR3 Cable Insulations

CR3 ID	Cable	SCRAPS Cable/Insulation ID	Exposure Conditions Investigated	
			Temperature (C)	Dose rate (Gy/h)
RCR296	Anaconda (FR-EP/CPE)	C-2/EPR-02	120, 140, 150, 160	0
			41	58.6
			60	330, 5140
			61	60.9
			80	133, 314, 790, 5290
			100	135, 226, 313, 810
			110	26.9
			115.6	98.5
			120	71.5, 125, 294, 420, 773, 5090
RCR283,4	BIW (EPR/CSPE)	---		
FWA75	Brand Rex (FR-XLPE/CSPE)	C-3/XLPO-02A, XLPO-02B	99, 109, 120, 125, 140, 150, 151.5, 160	0
			22	16.8, 124, 210
			40	215
			41	69
			60	317, 5240
			80	120, 323, 682, 5350
			100	25.4, 301, 700
			110	25.4, 150
			115	92.4
			120	90, 307, 664, 5030
ARE41	Kerite (HTK/FR)	---		

EFC51	Okonite (EP-FMR/CSPE)	C-18/EPR-05	99, 109, 124, 138	0
			40	430
			80	445
CIS1	Rockbestos (XLPE/CSPE)	C-16/XLPO-05	109, 124, 138, 150, 151, 160	0
			23	210
			40	215
			41	76
			60	360, 1850
			61	80
			80	353, 3710
			100	353
			120	62, 360

The EPRI Cable Polymer Aging Database (CPAD) Version 2.0 [EPRI 1011874] includes the SCRAPS data and addition exposure data on insulation materials from other sources. Although more research will be required to distinguish if CPAD cable formulations are identical to those in the CR3 lot, or merely similar formulations from the same manufacturers, CPAD entries exist for each of the CR3 cables as summarized in Table 3. As with the SCRAPS data in Table 2, entries with 0 dose rate represent thermal only aging. It may be noted that much of the gamma exposure data contributed by the University of Connecticut (UConn) was for very low, field service levels of dose rates. This is because the cable samples from that source were aged by placing them in representative locations with NPPs, not in a laboratory [EPRI TR-106845]. The CR3 cable materials in their as-received state may provide similar information if the dose rate and temperature of their environment during their decades of service may be determined. Accelerated aging of the CR3 materials will be performed at higher doses such as 50 to 100 Gy/h. The higher dose rate, artificially aged specimen entries from UConn apparently were exposed thermal aging and radiation sequentially, rather than simultaneously [EPRI TR-106845]. The UConn cable specimens were also apparently aged as intact cables, with preparation of test specimens from the cables performed after aging. This is in contrast to the Sandia approach in SCRAPS of aging prepared specimens.

Table 3. Summary of Information in CPAD 2.0 Database for CR3 Cable Insulations

CR3 ID	**Cable**	**CPAD 2.0 Cable ID**	**Exposure Conditions Investigated**	
			Temperature (C)	**Dose rate (Gy/h)**
RCR296	Anaconda (FR-EP/CPE)	UConn C	41	0
			39	0.009
			40	0.013, 0.024
			41	0.004, 0.012
RCR283,4	BIW (EPR/CSPE)	UConn ZB	41, 48, 132	0
			~30	0.004 - 0.04
			~40	0.002 - 0.02
			~50	0.004 - 0.08
			~60	0.001 - 0.08
			132	10000
FWA75	Brand Rex (FR-XLPE/CSPE)	UConn E (XLPE)	46	0.0042, 0.0238
			58	0.0140
			62	0.0029

		PSRC Srex3R (XLPE)	158	0, 2400
ARE41	Kerite (HTK/FR)	UConn ZK	132	0
			~30	0.003 - 0.03
			~40	0.0001 - 0.02
			~50	0.0001 - 0.1
			~60	0.001 - 0.1
			67	0.002
			132	10000
EFC51	Okonite (EP-FMR/CSPE)	UConn ZO	~30	0.004 - 0.03
			~40	0.0003 - 0.02
			~50	0.0004-0.08
			~60	0.001 - 0.08
			67	0.002
			132	10000
		PSRC Soko1B	150	0, 8600
CIS1	Rockbestos (XLPE/CSPE)	PSRC Sroc3B	150	0, 1500
		SKi 1	80, 95, 120, 142	0, 4500

Targeted total accumulated dose for each CR3 cable material will be identified based on reasonable project resource limits in time and budget and based on reported radiation dose stability of material class. For instance, reported transition from useful range to use not recommended in terms of total dose in Gray is ~$3x10^6$ for EPR and 10^6 for XLPE/XLPO [CERN 82-10]. Dose rates explored will be selected based on practical considerations such as time to target total dose. Number of intermediate data points for dose rates and total dose will be limited by the amount of test material on hand to generate required samples. Multiple temperature points below the lowest material phase transition will targeted if resources allow toward determination of activation energies most relevant to service conditions for most accurate remaining lifetime prediction. Aging research on the CR3 materials will fill gaps in the prior work referenced above including exposure at temperature and dose rates not previously investigated. In addition, thermal and radiation aging will be performed both simultaneously and independently to explore the relative and combined effects of the aging stresses. The work will be targeted toward addressing questions regarding the presence of inverse temperatures effects in cable aging, in which damage is more severe at lower temperatures, dose rate effects, in which damage for the same total may be more severe at lower dose rates, and inhomogeneous aging effects such as diffusion limited oxidation, in which too rapid of accelerated aging can misrepresent long term service aging [NUREG/CR-7153].

CONCLUSION

Harvested electrical cables from CR3 present a valuable opportunity to investigate simultaneous thermal and gamma irradiation aging on cable materials of highest relevance US NPP long term operation. Six of the ten most common insulation types are included. Information on cable locations and uses during service as well as cable source, installation information, etc. provide the rare chance to directly associate cable condition with service aging. Research on the cable materials harvested from CR3 will address cable aging knowledge gaps associated with synergistic thermal and gamma irradiation aging effects, inverse temperature effects, and uncertainty in activation energies [NUREG/CR-7153].

REFERENCES

CERN 82-10 *Compilation of Radiation Damage Test Data, Part III: Materials Used Around High-Energy Accelerators*. CERN European Organization for Nuclear Research. 1982.

EPRI 1011874. C-PAD 2.0 Cable *Polymer Aging Database: For Low Voltage Applications*, Version 2.0, EPRI, Palo Alto, CA, and U.S. Department of Energy, Washington, D.C.: 2002.

EPRI TR-103841.Revision 1. *Low Voltage Environmentally-Qualified Cable License Renewal Industry Report*. Electric Power Research Institute. 1994.

EPRI TR-106845 *Natural versus Artificial Aging of Electrical Components-Interim Report 1991-1995*. Electric Power Research Institute. 1997.

NUREG/CR-7153, Vol. 5. *Expanded Materials Degradation Assessment (EMDA) Volume 5: Aging of Cables and Cable Systems*. United States Nuclear Regulatory Commission. 2014.

SAND2005-7331 *Nuclear Energy Plant Optimization (NEPO) Final Report on Aging and Condition Monitoring of Low-Voltage Cable Materials*. Sandia National Laboratories. 2005.